

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☒ This express request to begin national examination procedures (35 U.S.C. 371(f) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1).
4. ☒ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. ☒ A copy of the International Application as filed (35 U.S.C. 371(c)(2))
 - a. ☒ is transmitted herewith (required only if not transmitted by the International Bureau).
 - b. ☐ has been transmitted by the International Bureau.
 - c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☐ A translation of the International Application into English (35 U.S.C. 371(c)(2)).
7. ☐ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3)).
 - a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
 - b. ☐ have been transmitted by the International Bureau.
 - c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
 - d. ☐ have not been made and will not be made.
8. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371 (c)(4)).
10. ☐ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371 (c)(5)).

Items 11. to 16. below concern document(s) or information included:

11. ☐ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. ☒ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. ☒ A FIRST preliminary amendment.
☐ A SECOND or SUBSEQUENT preliminary amendment.
14. ☐ A substitute specification.
15. ☐ A change of power of attorney and/or address letter.
16. ☒ Other items or information:
 - Formal Drawings (9 sheets)
 - Amendment Before First Office Action including
 - Marked-Up Amended Claims 2-6, 8 and 9 and
 - Clean/Replacement Claim Set
 - Postal Card

FORM PTO-1390
U.S. APPLICATION NO.
(if know, see 37 CFR 1.5):
Unknown

INTERNATIONAL APPLICATION NO.:
PCT/GB99/03711

09/831241
JC18 Rec'd PCT/PTO 03 MAY 2001
US
ATTORNEY'S DOCKET NUMBER:
R & G Case 321

17. ☒ The following fees are submitted:

CALCULATIONS PTO USE ONLY

BASIC NATIONAL FEE (37 CFR 1.492(a)(1)-(5)):

Neither international preliminary examination fee (37 CFR 1.482)
nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO
and International Search Report not prepared by the EPO or JPO \$1000.00
International preliminary examination fee (37 CFR 1.482) not
paid to USPTO but International Search Report prepared by
the EPO or JPO \$ 860.00
International preliminary examination fee (37 CFR 1.482) not
paid to USPTO but international search fee (37 CFR 1.445(a)(2))
paid to USPTO \$ 710.00
International preliminary examination fee paid to USPTO (37
CFR 1.482) but all claims did not satisfy provisions of PCT
Article 33(1)-(4) \$ 670.00
International preliminary examination fee paid to USPTO (37 CFR
1.482) and all claims satisfied provisions of PCT Article 33(1)-(4) ... \$ 100.00
ENTER APPROPRIATE BASIC FEE AMOUNT = \$860.00

Surcharge of \$130.00 for furnishing the oath or declaration later than ☐ 20 ☐ 30
months from the earliest claimed priority date (37 CFR 1.492(e)). \$

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE	
Total claims	9 - 20 =	0	X \$ 18.00	\$
Ind. claims	4 - 3 =	1	X 80.00	\$ 80.00
MULTIPLE DEPENDENT CLAIMS (if applicable)			+ \$270.00	\$
TOTAL OF ABOVE CALCULATIONS			=	\$940.00

Reduction of 1/2 for filing by small entity, if applicable. Small Entity Statement
must also be filed (Note 37 CFR 1.9, 1.27, 1.28). - \$
SUBTOTAL = \$940.00

Processing fee of \$130.00 for furnishing the English translation later than ☐ 20 ☐ 30
months from the earliest claimed priority date (37 CFR 1.492(f)). + \$
TOTAL NATIONAL FEE = \$940.00

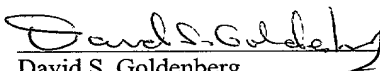
Fee for recording assignment (37 CFR 1.21(h)). The assignment must be accompanied
by an appropriate cover sheet (37 CFR 3.28, 3.31). \$40.00 per property + \$ 40.00
TOTAL FEES ENCLOSED = \$980.00
Amount to be refunded \$
charged \$

- a. ☒ A check in the amount of \$980.00 to cover the above fees is enclosed.
b. ☐ Please charge my Deposit Account No. _____ in the amount of \$ _____ to cover the above fees. A duplicate
copy of this sheet is enclosed.
c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to
Deposit Account No. 06-1382. A duplicate copy of this sheet is enclosed.

**NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a)
or (b)) must be filed and granted to restore the application to pending status.**

IN DUPLICATE

SEND ALL CORRESPONDENCE TO:
FLYNN, THIEL, BOUTELL & TANIS, P.C.
2026 Rambling Road
Kalamazoo, Michigan 49008-1699


David S. Goldenberg
Registration Number: 31 257

300.0900

09/831241

PATENT APPLICATION

JO18 Rec'd PCT/PTO 03 MAY 2001

Express Mail Label No.: EL 640 011 294 US

IN THE U.S. PATENT AND TRADEMARK OFFICE

May 3, 2001

Applicant: Simon PEARCE

For : TEXTURING SYSTEMS FOR USE IN
THREE-DIMENSIONAL IMAGING SYSTEMS

PCT International Application No.: PCT/GB99/03711

PCT International Filing Date: November 8, 1999

U.S. Application No.

(if known, see 37 CFR 1.5): Unknown

Atty. Docket No.: R&G C-321

Box PCT

Assistant Commissioner for Patents

Washington, DC 20231

PRELIMINARY AMENDMENT CANCELING CLAIMS

Sir:

Prior to calculation of the filing fee in the above-identified application, kindly enter the following:

IN THE CLAIMS

Please amend Claims 4-6 as shown on the attached marked-up page. Pursuant to 37 CFR § 1.121, a replacement page with the amended claims presented in clean form is also enclosed herewith.

REMARKS

This amendment cancels claims to reduce the filing fee. Please enter this amendment before calculating the filing fee.

Respectfully submitted,


David S. Goldenberg

DSG/smd

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Reg. No. 22 724
Reg. No. 32 549
Reg. No. 36 589
Reg. No. 31 257
Reg. No. 24 949
Reg. No. 40 694
Reg. No. 36 328

Encl: Marked-Up Amended Claims 4-6
Clean/Replacement Claims 4-6

4. (Amended) A texturing system according to claim 2-~~or 3~~, in which there are four cache means (60) and four decompression means (62) arranged in parallel.

5. (Amended) A texturing system according to claim 2, ~~3 or 4~~, further comprising allocating means (82) between the cache means (60) and the decompression means (62), for allocating the outputs of different caches to selected ones of the decompression means.

6. (Amended) A texturing system according to ~~any preceding claim~~Claim 1, in which the lower-level mip-map generator means comprises four interpolators which operate on 16 texels from the mip-map held in the cache means to provide four texels as from the next lower mip-map.

4. (Amended) A texturing system according to claim 2, in which there are four cache means (60) and four decompression means (62) arranged in parallel.

5. (Amended) A texturing system according to claim 2, further comprising allocating means (82) between the cache means (60) and the decompression means (62), for allocating the outputs of different caches to selected ones of the decompression means.

6. (Amended) A texturing system according to Claim 1, in which the lower-level mip-map generator means comprises four interpolators which operate on 16 texels from the mip-map held in the cache means to provide four texels as from the next lower mip-map.

PATENT APPLICATION
IN THE U.S. PATENT AND TRADEMARK OFFICE

May 3, 2001

Applicant : Simon PEARCE
Title : TEXTURING SYSTEMS FOR USE IN
THREE-DIMENSIONAL IMAGING SYSTEMS
Serial No. : Unknown Group: Unknown
Filed : Unknown Examiner: Unknown
International Application No.: PCT/GB99/03711
International Filing Date : November 8, 1999
Atty. Docket No.: R&G C-321

Assistant Commissioner for Patents
Washington, DC 20231

Sir:

Herewith is an amendment in the above-identified application.
[] Statement(s) re small entity status submitted previously.
[] Statement(s) re small entity status enclosed.
[X] No additional filing fee is required.
[] The additional filing fee has been calculated as shown below:

For	No. Filed	No. Extra	(X) LG Entity	RATE	() SM Entity	Fee
Basic Fee				\$710.00	\$355.00	\$
Total Claims	(12 - 20 = 0)		x	\$ 18.00	x \$ 9.00	
Indep. Claims	(4 - 4 = 0)		x	\$ 80.00	x \$ 40.00	
[] Multiple Dep. Claim			+	\$270.00	+	\$135.00
* * * TOTAL FILING FEE * * *						\$ 0.00

[X] A Check for \$980.00 is enclosed to cover fees.
[X] Please credit any overpayment, or charge any additional filing fee or application processing fee required under 37 CFR 1.16 or 1.17 by this communication, to Deposit Account No. 06-1382. A duplicate copy of this sheet is enclosed.

IN DUPLICATE

Respectfully submitted,

DSG/smd

David S. Goldenberg
David S. Goldenberg Reg. No. 31 257

Enclosures: Listed Above

PATENT APPLICATION

IN THE U.S. PATENT AND TRADEMARK OFFICE

May 3, 2001

Applicant : Simon PEARCE
 Title : TEXTURING SYSTEMS FOR USE IN
 THREE-DIMENSIONAL IMAGING SYSTEMS
 Serial No. : Unknown Group: Unknown
 Filed : Unknown Examiner: Unknown
 International Application No.: PCT/GB99/03711
 International Filing Date : November 8, 1999
 Atty. Docket No.: R&G C-321

Assistant Commissioner for Patents
 Washington, DC 20231

Sir:

Herewith is an amendment in the above-identified application.

- ☐ Statement(s) re small entity status submitted previously.
☐ Statement(s) re small entity status enclosed.
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For	No. Filed	No. Extra	(X) LG Entity	RATE	() SM Entity	Fee
Basic Fee				\$710.00	\$355.00	\$
Total Claims	(12 - 20 = 0)		x	\$ 18.00	x \$ 9.00	
Indep. Claims	(4 - 4 = 0)		x	\$ 80.00	x \$ 40.00	
[] Multiple Dep. Claim			+	\$270.00	+ \$135.00	
* * * TOTAL FILING FEE * * *						\$ 0.00

- ☒ A Check for \$980.00 is enclosed to cover fees.
☒ Please credit any overpayment, or charge any additional filing fee or application processing fee required under 37 CFR 1.16 or 1.17 by this communication, to Deposit Account No. 06-1382. A duplicate copy of this sheet is enclosed.

IN DUPLICATE

Respectfully submitted,

DSG/smd

David S. Goldenberg
 David S. Goldenberg Reg. No. 31 257

Enclosures: Listed Above

PATENT APPLICATION

Express Mail Label No.: EL 640 011 294 US

IN THE U.S. PATENT AND TRADEMARK OFFICE

May 3, 2001

Applicant: Simon PEARCE

For : TEXTURING SYSTEMS FOR USE IN
THREE-DIMENSIONAL IMAGING SYSTEMS

PCT International Application No.: PCT/GB99/03711

PCT International Filing Date: November 8, 1999

U.S. Application No.

(if known, see 37 CFR 1.5): Unknown

Atty. Docket No.: R&G C-321

Box PCT

Assistant Commissioner for Patents

Washington, DC 20231

AMENDMENT BEFORE FIRST OFFICE ACTION

Sir:

This paper is submitted simultaneously with the filing of the above identified application.

IN THE CLAIMS

Cancel Claims 1 and 7 without prejudice.

Amend Claims 2-6, 8 and 9 as indicated on the marked-up version of the claims submitted herewith.

Add Claims 10-14.

Pursuant to 37 CFR § 1.121, the Applicant submits a set of replacement claims that contains all the claims presently in this application, Claims 2-6 and 8-14.

REMARKS

This paper is submitted simultaneously with the filing of this application.

At this time, the Applicant cancels Claims 1-7, amends Claims 2-6, 8 and 9, and adds new Claims 10-14. Claims 8, 9, 10 and 14 are the independent claims of this application.

Claim 10 corresponds to the amended version of Claim 1 that was the subject of the International Preliminary Examination Report for the PCT application upon which this

application is based. Claims 2-6 and 11-13 are dependent from Claim 10.

Claim 14 corresponds to the amended version of Claim 7 that was the subject the International Preliminary Examination Report.

The Applicant notes that the International Preliminary Examination Report stated that, in the opinion of the International Preliminary Examining Authority, all of the claims in the PCT application are directed to an invention that is both novel and the result of an inventive step over the prior art.

Respectfully submitted,


David S. Goldenberg

DSG/smd

FLYNN, THIEL, BOUTELL	Dale H. Thiel	Reg. No. 24 323
& TANIS, P.C.	David G. Boutell	Reg. No. 25 072
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Phone: (616) 381-1156	Mark L. Maki	Reg. No. 36 589
Fax: (616) 381-5465	David S. Goldenberg	Reg. No. 31 257
	Sidney B. Williams, Jr.	Reg. No. 24 949
	Liane L. Churney	Reg. No. 40 694
	Brian R. Tumm	Reg. No. 36 328

Encl: Marked-Up Amended Claims 2-6, 8 and 9
Clean/Replacement Claim Set

336.9804

2. (Amended) AThe texturing system according to claim 110, including decompression means ~~(32,62)~~ for decompressing mip-map data, the mip-map data being stored in the memory means in compressed form.

3. (Amended) AThe texturing system according to claim 2, in which the decompression means ~~(32,62)~~ is connected with its input coupled to the cache means and its output coupled both to the trilinear interpolator means and to the lower-level mip-map generator means.

4. (Twice Amended) AThe texturing system according to claim 2, in which there are four cache means ~~(60)~~ and four decompression means ~~(62)~~ arranged in parallel.

5. (Twice Amended) AThe texturing system according to claim 2, further comprising allocating means ~~(82)~~ between the cache means ~~(60)~~ and the decompression means ~~(62)~~, for allocating the outputs of different caches to selected ones of the decompression means.

6. (Twice Amended) AThe texturing system according to Claim 110, in which the lower-level mip-map generator means comprises four interpolators which operate on 16 texels from the mip-map held in the cache means to provide four texels as from the next lower mip-map.

8. (Amended) Apparatus for generating texture data for use in texturing an image, comprising the steps of:

means for representing texture data by arbitrary compressed codes, in which selected compressed

code values define principal colors and other compressed code values define colors which can be formed by selected weighted averages of principal colors, the corresponding code values also being weighted averages of the code values of the selected principal colors; and

interpolating means for interpolating an output texel from a plurality of input texels;

characterized in that:

the interpolating means effects the interpolation using compressed code values.

9. (Amended) A method of generating texture data for use in texturing an image, comprising the steps of:

representing texture data by arbitrary compressed codes, in which selected compressed code values define principal colors and other compressed code values define colors which can be formed by selected weighted averages of principal colors, the corresponding code values also being weighted averages of the code values of the selected principal colors;

interpolating an output texel from a plurality of input texels;

characterized in that:

the interpolating step is effected using compressed code values.

10. (New) A texturing system for use in a three-dimensional imaging system, and comprising:

memory means for storing mip-map data for use in texturing an image, the mip-map data comprising a hierarchical series of mip-maps of different levels of decreasing resolution;

input means for receiving input data indicating the type of mip-map data required and the level of the mip-map or mip-maps from which the data is to be taken;

control means coupled to the input means and to the memory means for retrieving from memory the mip-map data required in accordance with the input data; and

cache means coupled to the control means for storing portions of mip-map data retrieved from memory and relating to a selected mip-map level;

lower-level mip-map generator means coupled to the cache means for generating portions of the mip-map next below in the hierarchical series of mip-maps of which portions are held in the cache means; and

trilinear interpolator means coupled to the cache means to receive mip-map data from one level of mip-map and to the lower level mip-map generator to receive mip-map data from the mip-map next below in the hierarchical series and to interpolate an output texel from input texels from the two received mip-map levels.

2. (Amended) The texturing system according to claim 10, including decompression means for decompressing mip-map data, the mip-map data being stored in the memory means in compressed form.

3. (Amended) The texturing system according to claim 2, in which the decompression means is connected with its input coupled to the cache means and its output

coupled both to the trilinear interpolator means and to the lower-level mip-map generator means.

4. (Twice Amended) The texturing system according to claim 2, in which there are four cache means and four decompression means arranged in parallel.

11. (New) The texturing system of Claim 4, further comprising allocating means between the cache means and the decompression means, for allocating the outputs of different caches to selected ones of the decompression means.

12. (New) The texturing system of Claim 4, in which the lower-level mip-map generator means comprises four interpolators which operate on 16 texels from the mip-map held in the cache means to provide four texels as from the next lower mip-map.

5. (Twice Amended) The texturing system according to claim 2, further comprising allocating means between the cache means and the decompression means, for allocating the outputs of different caches to selected ones of the decompression means.

13. (New) The texturing system of Claim 5, in which the lower-level mip-map generator means comprises four interpolators which operate on 16 texels from the mip-map held in the cache means to provide four texels as from the next lower mip-map.

6. (Twice Amended) The texturing system according to Claim 10, in which the lower-level mip-map generator means comprises four interpolators which operate on 16

texels from the mip-map held in the cache means to provide four texels as from the next lower mip-map.

8. (Amended) Apparatus for generating texture data for use in texturing an image, comprising the steps of:

means for representing texture data by arbitrary compressed codes, in which selected compressed code values define principal colors and other compressed code values define colors which can be formed by selected weighted averages of principal colors, the corresponding code values also being weighted averages of the code values of the selected principal colors; and

interpolating means for interpolating an output texel from a plurality of input texels;

characterized in that:

the interpolating means effects the interpolation using compressed code values.

9. (Amended) A method of generating texture data for use in texturing an image, comprising the steps of:

representing texture data by arbitrary compressed codes, in which selected compressed code values define principal colors and other compressed code values define colors which can be formed by selected weighted averages of principal colors, the corresponding code values also being weighted averages of the code values of the selected principal colors;

interpolating an output texel from a plurality of input texels;

characterized in that:

the interpolating step is effected using compressed code values.

14. (New) A method of texturing for use in three-dimensional imaging, and comprising the steps of:

storing in memory mip-map data for use in texturing an image, the mip-map data comprising a hierarchical series of mip-maps of different levels of decreasing resolution;

receiving input data indicating the type of mip-map data required and the level of the mip-map or mip-maps from which the data is to be taken;

retrieving from memory the mip-map data required in accordance with the input data;

storing in a cache portions of mip-map data retrieved from memory and relating to a selected mip-map level; and

generating in real-time portions of the mip-map next below in the hierarchical series of mip-maps of which portions are held in the cache means; and

interpolating an output texel from input texels from the mip-map level stored in the cache and the mip-map next below in the heirarchical series generated in real time.

9/PRTS

- 1 -

TEXTURING SYSTEMS FOR USE IN
THREE-DIMENSIONAL IMAGING SYSTEMS

Field of the Invention

5 This invention relates to texturing systems for use
in three-dimensional imaging systems, such as are used in
computer displays. Such texturing systems are for example
employed in the display of computer games.

Prior Art

10 The following prior documents and materials should be
referred to for further information on the background to
this technology. Certain of them are referred to where
convenient by number in the subsequent description:

- [1] Catmull, E., "A Subdivision Algorithm for Computer
Display of Curved Surfaces", Ph.D. Thesis, report
15 UTEC-Csc-74-133, Computer Sciences Department, University
of Utah, Salt Lake City, UT, December 1974.
- [2] Blinn, J.F. and M.E. Newell, "Texture and Reflection
in Computer Generated Images", CACM, 19(10), October 1976,
542-547.
- 20 [3] Wolberg, G., "Digital Image Warping", IEEE Computer
Society Press, Los Alamitos, CA, 1990.
- [4] Williams, L., "Pyramidal Parametrics", SIGGRAPH 83,
pages 1-11.
- [5] VideoLogic, "Apocalypse 3Dx data", available from
25 VideoLogic Limited, Kings Langley, England.
- [6] Microsoft Corporation, "Texture and Rendering Engine
Compression (TREC)", Microsoft Technical Brief, internet
address: www.microsoft.com/hwdev/devdes/whntrec.htm
- [7] Beers, A. C. Agrawala, M. and Chaddha, N., "Rendering
30 from Compressed Textures", 1996 Computer Graphics Annual
Conference, page 373.

- 2 -

[8] Hakura, Z.S. and Gupta, A. "The design and analysis of a cache architecture for texture mapping", Computer Architecture News, Vol.25, no.2, pp.108-20, May 1997.

[9] United States Patent US-A-5,612,747 "Method and apparatus for vector quantization caching in a real time video coder".

[10] United Kingdom Patent Application GB-A-2,297,886 "Texturing and shading of 3-D Images ", Applicants: VideoLogic Limited.

[11] Gray, R. M., "Vector Quantization", IEEE Transactions on Communications, January 1980, pp.4-20.

[12] Koegel Buford, J., "Multimedia Systems", Addison-Wesley publishing company, 1994.

[13] Foley, F. and van Dam, A., "Computer Graphics Principles and Practice", Addison-Wesley publishing company, 1990.

[14] Microsoft, "DirectX 6.0 SDK Documentation", Microsoft Corporation, 1 Microsoft Way, Redmond, USA. Internet address: www.microsoft.com/directx.

Background of the Invention

Computer based images are commonly formed of an array of picture elements or pixels. Each surface to be displayed may be represented by the pixels within a polygon, commonly a triangle. The surface is given color, texture and/or shading by an operation known as "texture mapping". Textures are stored as arrays of pixels, conveniently termed texels (texture pixels). Thus "texture mapping" involves the mapping of a 2D (two-dimensional) array of texels onto another 2D array of pixels representing a surface in a 3D (three-dimensional) scene. This technique was developed by Catmull [ref. 1] and refined by Blinn and Newell [ref. 2]. Perspective texture mapping involves rotating and translating the texture map so that its perspective appears correct on the

- 3 -

final image. Texture mapping improves the realism of the scene by giving the surface of an object a realistic finish. An example of this is mapping a marble texture to the surface of a statue, giving the statue the appearance that it is made of marble. For a large scene many different texture bitmaps are required to represent all the different textures which might be present in the scene.

As just noted, a 3D scene is usually represented by a number of polygons or triangles. In order to fill a polygon with a texture, each pixel on its surface is used to calculate the co-ordinate of a texel in the texture map. The nearest texel to the one calculated in the texture map may be used to shade the finally displayed pixel. This is called point sampling. Alternatively, bilinear filtering or bilinear interpolation may be used to improve the quality of the textured image. In bilinear filtering the point in the texture map from which the 2D pixel is to be mapped onto the 3D surface is calculated to sub-pixel accuracy. Bilinear filtering or interpolation is then used to blend the four closest pixels to this calculated position in the texture map in order to attain a more accurate representation of the pixel color. This is illustrated in the accompanying Figure 1, where the texels A, B, C, and D are blended to provide a texel value for a pixel at point X on the two-dimensional image plane. This operation of bilinear, i.e. two-axis, filtering (or interpolation) is further described in ref. 3.

Trilinear (three-axis) filtering is the same process over the four closest pixels on two different mip-map levels [ref. 4]. This is illustrated in Figure 2 of the present application. Mip-maps are copies of the original texture map which have been pre-processed by being filtered so as to be successively reduced to half the resolution. MIP here stands for MULTUM IN PARVO (much in

- 4 -

a small place). This is repeated until the resulting image is 1 pixel in size (this assumes that the texture is square and of a size which is a power of 2), so that there are a hierarchical series of the mip-maps. Figure 3 shows an example of a brick texture at 128 x 128 resolution with the associated lower mip-map levels. A mip-map can be thought of as a pyramid.

Texture filtering has the effect of reducing the occurrence of aliasing when sampling textures. For more information on aliasing see ref. 3.

Three-dimensional image generation is computationally intensive. Animated 3D images for games and Computer Aided Design (CAD) applications are becoming increasingly expensive in terms of processing power, as scenes become more photo-real and images are required to respond in real-time. A large number of floating point calculations are required to determine the geometry of the polygon structure in the scene and a large number of arithmetic operations are required to fill and shade the polygons. Dedicated hardware is available [ref. 5] that can perform these operations many times more efficiently than software. Accesses to stored databases are also a limiting factor to performance. Local memory in dedicated hardware can reduce the effect of any memory access bottlenecks. Texture mapping is particularly memory intensive especially when performing a filtering (that is, interpolation) operation where many texture pixels are read for every pixel that is mapped onto the display.

The size of a 2D texture map data is therefore reduced by texture compression so that it can be located into a smaller memory space. A small memory requirement leads to lower system costs. The original texture map can then be retrieved from the compressed data by decompression. As 3D scenes become more realistic, texture maps become larger and more numerous, making the

- 5 -

use of texture compression more important. Several schemes have already been developed including Texture and Rendering Engine Compression (TREC) from Microsoft [ref. 6]. Beers [ref. 7] first discussed the technique of rendering images from compressed textures.

It is convenient at this point to consider, and define, the various types of memory that are available to the system designer. The term "local memory" refers to solid state semiconductor memory located close to the memory control semiconductor device or circuit. The term "internal memory" refers to memory located within the particular semiconductor device being referred to. "External memory" is any memory outside the semiconductor device. Local memory can be DRAM based. DRAM is an acronym for Dynamic Random Access Memory, which is a solid-state semiconductor. Synchronous DRAM (SDRAM) enables data accesses to be co-ordinated by a clock signal. SDRAM has a higher access bandwidth capability than DRAM due to its pipelined architecture but is more expensive. Local memory and internal memory can be DRAM or SDRAM based. External memory can be sold-state or a mass storage array such as a hard disk. Semiconductor memory is very expensive and makes up a large percentage of the overall cost of a computer system.

DRAM is addressed over a multiplexed address bus, that is, the address needed to access an individual data item is transmitted to the memory device in two parts. The core memory array in the DRAM device is a rectangular matrix where a single data item is addressed when a row control line and a column control line are activated at the same time. This requires a separate row and column address. If the row address does not change between sequential accesses, then only the column address needs to be transmitted. A row of data in the DRAM array is known as a page. When the row address remains unchanged between

- 6 -

accesses, the accesses are said to be "in page". "In page" accesses are much quicker than those that span two or more pages, and memory system designers endeavour to keep bursts of accesses in page. Some memory devices, such as SDRAM, make use of multiple memory banks to improve performance. Each memory bank can have its own page open, permitting data accesses to separate areas of memory without breaking page.

One technique used to improve memory performance is "Memory Caching" in which the result of all external memory accesses is stored in a separate internal memory. This internal memory can be accessed much faster than external memory. If the result of a particular memory access already resides in the cache, then the cache is read instead of the external memory. This has the effect of reducing traffic to the external memory, and therefore reducing the "bandwidth" requirements of that memory. The bandwidth requirement of a memory system is often directly related to the cost of that system. In a fixed bandwidth system an increased bandwidth requirement can lead to a reduction of overall system performance.

Texturing is the most performance-intensive process of 3D imaging as it requires all textures to be retrieved from memory. Techniques such as trilinear and bilinear filtering (interpolation) require up to eight texture pixels or texels to be retrieved from memory for every pixel projected onto the display, as described above and illustrated in Figures 1 and 2. Texturing therefore requires a very high bandwidth path into memory. Texture caching can be employed to reduce the texturing bandwidth requirement and increase system performance. The optimum performance objective is to be able to read all necessary texels in one processing pipeline clock cycle. Some work has already been done on studying the effects of using a cache to improve the performance of texture accesses

- 7 -

[ref. 8]. Hakura demonstrates how caches can be highly effective for texture mapping graphics, and concludes that the effective memory to bandwidth ratio can be reduced by a factor of three to fifteen using certain caching strategies.

As previously indicated, texture mapping is used to improve 3D image quality by mapping high detail onto a surface of a 3D object. This should be done without complicating the object's geometry. However, texture mapping produces a wide variety of visual artefacts, including aliasing [ref. 13]. Bilinear filtering [ref. 3] is used to improve the quality of the resulting image but there remain many artefacts that bilinear filtering cannot solve, including depth aliasing. Depth aliasing is the result of the texture getting more compressed as an object moves further from the viewpoint. This form of aliasing can be resolved by use of mip-maps [ref. 4], but there is still a problem called mip-banding. Mip-banding occurs during the transition period between mip-maps when the texture changes from one level of detail to another. This may appear for example on a road, seen in the foreground, which disappears into the distance. Successive mip-maps are used along the road and the transition from one mip-map to the next can be visible. This problem can be solved with the application of trilinear filtering [ref. 4], which interpolates the level of detail between mip-maps, as described above.

The best form of trilinear filtering is that which is performed on a per-pixel basis. This requires eight texture pixels (texels) to produce the final on-screen pixel. As these texels can be located anywhere in memory, eight separate memory reads are often required. Trilinear filtering is performed between two mip-levels, and so four memory reads occur from one mip-map location and four from another. Textures are usually stored in local memory,

- 8 -

although system memory texturing is becoming more popular. These memories have a finite bandwidth and are very often required to serve as a resource to memory for many different applications. Set-up parameters, depth
 5 information, and display information are usually stored in local memory, and system applications are usually run from system memory. Eight individual memory reads per pixel is usually beyond the capabilities of many memory systems. Added to page change between mip-maps, this often achieves
 10 less than adequate 3D performance.

The memory bandwidths required for a trilinear texture access system is dependent on the number of memory accesses needed for each texture filtering operation and the pixel throughput performance demanded by the
 15 application. Equation 1 shows how the texture bandwidth can be determined. The equation also shows how the bandwidth of page breaks must also be taken into account.

$$Bandwidth_{texture} = ((Accesses_{pixel} \times Width_{memory}) + (Accesses_{page_break} \times Width_{memory})) \times Throughput_{pixel}$$

... Equation (1)

Where:

20 $Bandwidth_{texture}$ is the texture bandwidth demanded from the memory measured in bytes/s. This is not the memory bandwidth that can be supplied by the memory.

$Accesses_{pixel}$ is the average number of memory accesses per pixel. Not all the required texels can be read in
 25 one access, even with the right data width.

$Accesses_{page_break}$ is the average number of memory access slots lost to page breaks per pixel. A single page break using SDRAM requires at least 8 accesses slots.

$Width_{memory}$ is the width of the memory data bus, measured in
 30 bytes. This has to be at least 8 bytes (64 bits) to

- 9 -

ensure that four texels can be read in one clock cycle.

$Throughput_{pixel}$ is the pixel throughput demanded by the application, measured in pixels/s. For most modern applications this is around 100 Mpixels/s.

The average accesses per pixel is the number of separate memory accesses required to retrieve all data necessary for the filtering operation. Using a 64-bit memory bus, maximum throughput is achieved if four 16-bit texels are required and they reside in the same data word. Unfortunately this is not always the case and very often the texture data resides in two or four separate words. Equation 2 shows how $Accesses_{pixel}$ can be found, taking into account the varying number of accesses for a single texture operation.

$$Accesses_{texture} = \frac{((Percentage_{single} \times 1) + (Percentage_{double} \times 2) + (Percentage_{quadruple} \times 4) \times Mipmaps)}{Factor_{compression}}$$

... Equation (2)

Where:

$Percentage_{single}$ is the percentage of single mip-map accesses that can be retrieved in one memory access.

$Percentage_{double}$ is the percentage of single mip-map accesses that can be retrieved in two memory accesses.

$Percentage_{quadruple}$ is the percentage of single mip-map accesses that can be retrieved in four memory accesses.

$Mipmaps$ is the number of mip-maps involved in the filter operation.

$Factor_{compression}$ is the compression factor if the texture is compressed.

- 10 -

The average number of accesses is calculated by taking into account the likelihood that all data will be retrieved in single, double or quadruple accesses. The equation also takes account of the number of mip-maps required in the filtering operation, trilinear filtering uses two but bilinear requires only one. The equation also shows how the average number of accesses is reduced linearly with compression. Obviously the less data there is to fetch the less memory accesses that are required and the more likely all the data will reside in the same data word.

Equation 1 thus shows that, even with the use of texture caches, the physical memory bandwidth requirement still remains beyond the scope of any viable memory system. For this reason texture compression is employed, not only to reduce the physical size of the stored texture, with its associated reduction in memory cost, but also to reduce the volume of texture data that is transferred from that memory.

Equation 2 shows how the compression factor affects the number of memory accesses. High performance, dedicated hardware can be used to decompress the textures in real-time after they have been read from memory. Many texture compression techniques have been tried, including: Vector Quantisation (VQ) [ref. 11]; Color lookup tables (CLUT) or Palletisation [ref. 12]; Discrete Cosine Transformation (DCT) [ref. 12]; and several proprietary techniques [refs. 6 and 14]. But each has its associated problems: VQ and Palletised require two memory reads or large internal data caches and quality can be limited; DCT requires a large amount of decompression logic, and with a limited silicon budget this can be unfeasible; and many proprietary techniques provide limited compression ratios and quality. As Equation 1 demonstrates, these techniques

- 11 -

only go part way towards resolving the bandwidth requirements of trilinear filtering.

Memory access streams that continuously swap between different memory banks can have a large effect on performance. Equation 1 shows how dominant page breaks are to the performance of texture filtering as a whole. For trilinear filtering, page breaks can be particularly problematic, where a number of mip-maps can often span more than one memory page.

3D imaging techniques often demand such a high level of performance that only dedicated hardware solutions can be used. This often requires the development of a special silicon chip. As well as performing texture mapping, the chip will often be called upon to perform all the geometry processing, polygon set up, image projection, illumination calculations, fogging calculations, hidden surface removal, and display control. Therefore it is critical that each stage in the generation of a 3D image is made as small as possible to enable all processes to fit on the same silicon die. As well as requiring a large memory bandwidth, a trilinear filtering operation can only be implemented in a large amount of logic and therefore silicon area. It is important that an optimum solution be found that limits the required logic, and therefore cost, to a minimum.

It is seen from the foregoing that the requirements of memory, speed and ease of construction of the chip are very substantial and are taxed to the full in 3D imaging, particularly when texture mapping. Even using all available techniques for meeting the requirements, the constraints are still very difficult to meet if high quality real-time imaging is to be achieved.

- 12 -

Summary of the Invention

The invention in its various aspects is defined in the independent claims below, to which reference should now be made. Advantageous features are set forth in the
5 appendant claims.

Preferred embodiments of the invention are described below with reference to the drawings. In these
10 embodiments the efficiency of trilinear texture filtering is improved by the generation of the lower-level texture mip-map on the fly from the upper-level mip-map, and with the use of texture caching and texture decompression as a means of meeting the high memory bandwidth requirements. Removing the need to read the lower-level mip-map in a
15 separate memory access, removes page break problems and enhances performance.

More particularly, the preferred texturing systems comprise a memory for storing mip-map data for use in
20 texturing an image, the mip-map data comprising a hierarchical series of mip-maps of different levels of decreasing resolution. Data is received at an input indicating the type of mip-map data required and the level of the mip-map or mip-maps from which the data is to be taken. A controller retrieves from the memory the mip-map data required in accordance with the input data, and this
25 data is stored in a cache. A lower-level mip-map generator generates portions of the mip-map which is next below, in the hierarchical series, the mip-map of which portions are held in the cache. A trilinear interpolator receives from the cache mip-map data from one level of
30 mip-map and from the lower-level mip-map generator data from the next lower level of mip-map, and interpolates one output texel from input texels from the two mip-map levels.

Some data compression schemes lend themselves well to
35 the generation of lower mip-maps on the fly by providing

- 13 -

the required quantity of decompressed data and by closely supporting the filtering algorithm used to generate the lower-level mip-map. These techniques may be used to enhance the performance and quality of a 3D rendered image while minimising the hardware overhead.

In one preferred embodiment, the texture data is represented by arbitrary compressed codes, in which selected compressed code values define principal colors and other compressed code values define intermediate colors which can be formed by selected weighted averages of principal colors, the corresponding code values also being weighted averages of the code values of the selected principal colors. The lower-level mip-map generator interpolates an output texel from a plurality of input texels by operating on the compressed code values.

Brief Description of the Drawings

The invention will now be described in more detail, by way of example, with reference to the drawings, in which:

Figure 1 is a diagram illustrating bilinear filtering of the texture map in an imaging system;

Figure 2 is a similar diagram illustrating trilinear filtering of the texture map in an imaging system;

Figure 3 illustrates a series of mip-maps;

Figure 4 is a block schematic diagram of part of an imaging system in accordance with the present invention;

Figure 5 is a diagram illustrating the operation of the embodiment of Figure 4;

Figure 6 illustrates the storage of texture words in a worst-case scenario;

Figure 7 is a block schematic diagram similar to Figure 4 of a second embodiment of the invention using four caches and four decompression units in parallel;

- 14 -

Figure 8 illustrates in similar manner to Figure 6 the storage of texture words in a best-case scenario;

Figure 9 is a block diagram of a modification of the embodiment of Figure 7, in which the decompression units are dynamically re-allocated;

Figure 10 is a block diagram of another modification of the circuit of Figure 7; and

Figures 11 and 12 illustrate how interpolation can be directly applied to compressed texture codes.

Detailed Description of the Preferred Embodiments

Figure 4 shows a specific embodiment of a texturing system in accordance with the invention. The texturing system 20 comprises a memory system 22 forming part of the memory used by the imaging system as a whole, and which is controlled in known manner by a memory controller 24. The memory 22 holds *inter alia* a compressed texture map, and the output of the memory through the memory controller 24 consists of compressed texture from the requested part of the texture map. Parameters defining the texture required for any surface are received at an input 26 and applied to a texture address generator 28 to address the part of the memory 22 where the desired texture is located. The compressed texture is retrieved from memory by the memory controller 24 and held in a texture cache 30. The retrieved texture will correspond to a particular texture type representing the type of surface to be displayed. For example this may be part of a brick wall or the surface of a road. This surface texture will be held in mip-map form, as described above, actually in compressed mip-map form, and the mip-map which is used will be the one which is the next in front of the surface, account being taken of the distance of the surface from the observer.

- 15 -

The output from the texture cache 30 is applied to a decompression unit 32, which decompresses or decodes the texture values to provide decompressed texels. The decompressed texels are then applied both to a trilinear interpolator 34 and to a generator 36 for generating the relevant part of the next lower mip-map to that held in the texture cache 30. The output of the generator 36 is also applied to the trilinear interpolator 34. Thus the interpolator receives the texels from the mip-map in front of and that behind the surface point under consideration, so that a trilinear interpolation, as illustrated in Figure 2, can be executed. The trilinear interpolator provides a trilinear-textured pixel at an output 38.

In operation, therefore, the texture address generator 28 feeds the addresses of the eight trilinear texels to the texture cache 30, which then fetches the associated compressed texture data from memory 22. The decompression unit (DU) 32 then decompresses 16 upper mip-map texels from the compressed data. Four are selected as the requested upper-level texels, and all 16 are used by the lower mip-map generator 36 to generate the lower-level mip-map texture. This is because four upper-level texels will be used to generate each lower-level texel, as described below. These upper-level and lower-level mip-maps are then used by the trilinear interpolator 34 to generate the single trilinear pixel. Although as many as 16 texels are required for this technique to work, which, uncompressed, would represent a large memory bandwidth, when compressed this represents a considerable memory bandwidth improvement with minimum page breaks.

The lower-level mip-map is generated by four parallel filters or interpolators 40 that are able to take the 16 upper-level texels and generate the four lower level in one clock cycle. Figure 5 illustrates this process. Out

- 16 -

of the 16 original texels, four are decoded to produce the four upper-level texels which are directly used for trilinear filtering. These 16 are also divided into four quadrants, each containing four pixels, which are then
5 filtered by four digital low-pass filters to produce the four lower-level mip-map texels required for trilinear filtering. This filtering algorithm is shown in Equation 3:

Lower-level color value0 = (upper0 + upper1 + upper4 + upper5) / 4
10 Lower-level color value1 = (upper2 + upper3 + upper6 + upper7) / 4
Lower-level color value2 = (upper8 + upper9 + upper12 + upper13) / 4
Lower-level color value3 = (upper10 + upper11 + upper14 + upper15) / 4
... Equation (3)

By applying actual values to Equation 1 and Equation
15 2, the cost of trilinear filtering can be determined. It has been determined that in a conventional system, four accesses of 64-bit data are required for each trilinear pixel when uncompressed, with an average of two page breaks per pixel. This gives a total bandwidth
20 requirement of 16 Gbytes/second for a system that must produce 100 Mpixels per second. Such performance is unacceptable, but even when the texture data is cached and compressed the bandwidth demanded is not much better
(13.2 Gbytes/s). However, when the double page break is
25 removed by generating the lower mip-map "on the fly" in the generator 36 of Figure 4, in accordance with this invention, the bandwidth is reduced to an acceptable level. Cached and compressed texture bandwidth
30 requirements for this system are of the order of only 200 Mbytes/s. A 64-bit memory system running at 100 MHZ has a peak bandwidth capability of 800 Mbytes/s, so the required 200 Mbytes/s is well within its capacity. Indeed, the lower-level mip-map construction system

- 17 -

embodying the invention can leave spare bandwidth which will be available for other uses.

In summary, therefore, it will be seen that the texturing system of Figure 4, which is designed for use as part of a three-dimensional imaging system, includes the memory 22 for storing mip-map data for use in texturing an image, the mip-map data comprising a hierarchical series of mip-maps of different levels of decreasing resolution. The input 26 receives input data indicating the type of mip-map data required, and the level of the mip-map or mip-maps from which the data is to be taken. The controller 24 is coupled to the input and to the memory for retrieving from memory the mip-map data required in accordance with the input data. The cache 30 is coupled to the controller for storing portions of mip-map data retrieved from memory which relate to a selected mip-map level. The trilinear interpolator 34 is coupled to the cache to receive mip-map data from one level of mip-map, namely the upper level of the two levels from which data is needed, and to interpolate an output texel from input texels from two mip-map levels. In accordance with the invention, the texturing system also includes the lower-level mip-map generator 36 which is coupled between the cache and the trilinear interpolator, and generates in real-time portions of the mip-map next below (in the hierarchical series) the mip-map of which portions are held in the cache.

The embodiment of the invention illustrated in Figure 4 shows how one cache 30 and one decompression unit (DU) 32 are required to return all data necessary to construct a complete trilinear interpolated pixel. A problem exists, however, when the filter algorithm needs data from two or four additional data words. Figure 6 shows the worse case situation. Consider the texture bitmap divided into tiles, with each tile representing the

- 18 -

texture pixels provided by one compressed data word. In this example the data word contains 16 texture pixels. The darker outlined boxes in Figure 6 represent the tiles. In this example, the filter algorithm requires texture
5 pixels from four separate compressed data words. For a single cache/decompression system, this worst case situation requires four cache reads and therefore a minimum of four clock cycles. This problem also exists, to a lesser extent, when two separate data words are
10 required.

A four-cache and four-DU construction can provide all requisite data in one clock period, no matter where the compressed data resides. Figure 7 shows a block diagram of a second embodiment of the invention which comprises
15 such a 'quad cache' arrangement. The texturing system of Figure 7 is similar to the system of Figure 4 and only the differences will be described in detail. In the second embodiment of Figure 7, the memory system 22 and input 26 are the same as in Figure 4. In this case the texture
20 address generator 28 has four outputs to cope with the situation where the outputs of a maximum of four tiles are required. The four outputs provide respectively texture addresses 1 to 4, and these are applied to texture caches 1 to 4, referenced 60. These communicate to and from the
25 memory controller 24 through an arbiter 58, so as to receive the texels from the four tiles respectively. These are held in the four caches, which thus output four cached compressed textures, namely cached compressed texture 1 to 4 respectively.

30 The outputs of the four caches 60 are respectively applied to four decompression units 62, each similar to the decompression unit of Figure 4. Each decompression unit 62 applies its decompressed data to upper and lower decode units 68,70, and also to a low-level mip-map filter

- 19 -

66. The outputs of the upper and lower decode units 68,70 are respectively applied to a trilinear interpolator 64.

In operation, each cache 60 is responsible for a different segment of the memory, based on the size of a cache word and the lower two bits of the texture address representing each cache word. In this way it can be guaranteed that a single cache will not be called upon to provide more than one data word for a complete trilinear pixel.

Without being able to generate the lower-level mip-map from the upper one, eight caches and DUs would be required, four for the upper map and four for the lower map. Thus, the generation of lower-level mip-maps as required 'on the fly' saves logic (silicon area) as well as improving performance. When coupled with compression, the amount of data required is also greatly reduced.

It will be appreciated that the lower-level mip-maps are still stored in the memory. They will be required for pixels which are yet further away from the viewer. However, it proves to be more efficient in the trilinear interpolation to ignore their presence and to regenerate those texels which are needed for the pixels being processed using the generators 62.

One of the major advantages of generating lower-level mip-maps from compressed upper-level mip-maps is the amount of logic optimisation that can take place. Less logic leads to smaller hardware and lower cost. One such area of optimisation is in the caches and decompression units.

The caches 60 for the quad cache system are effectively memory mapped, i.e. each cache holds data for a separate tile of texture memory, as noted above. However, the DUs 62 do not necessarily have to be memory mapped as well. Memory mapping of DUs would require that each is associated with a particular cache. This would

- 20 -

also necessitate each DU being able to produce at least four upper-level texels as well as four lower-level texels in one cycle to cater for the best case situation. The best case situation is illustrated in Figure 8 where all the tiles come from one data word.

By allowing each DU to be dynamically reallocated based on the resources required, then several hardware optimisations can take place to dramatically reduce the size of the hardware required. We have determined that not more than one unit need provide four parallel upper-level texels, not more than two units need provide two parallel upper-level texels, and none need provide more than one lower-level texel.

Figure 9 shows how these optimisations fit into a modified quad cache system. The modified arrangement of Figure 9 is similar to the arrangement of Figure 7 and only the differences need be described. These are the inclusion of a decompression unit (DU) allocator 82, which is connected between the outputs of the four caches 60 and the inputs of the four decompression units 62, and a corresponding deallocator 84, which replaces the upper and lower decode units 68,70 and is connected between the outputs of both the four DUs 62 and the filters 66, and the inputs to the trilinear interpolator 64. The DUs 62 are no longer identical; the primary DU can provide four parallel upper-level texels, the secondary DU can provide two parallel upper-level texels, and the tertiary and quadra DU can each provide only one upper-level texel. The DU allocation unit 82 determines which of the DUs 62 are required, based on the configuration of the texture addresses. Logic reduction takes place both on the registered outputs of each DU and the multiplexing of the texture output from each DU. The deallocation unit 84 now takes over from the upper and lower decode units 68,70, this time returning the dynamically allocated resource

- 21 -

data to the data paths that originally requested the texels. The arithmetic used to filter the four lower-level mip-map texels is also simplified.

The outputs are shown as being deallocated by the deallocator 84, but this may not be necessary depending on the manner in which the output of the trilinear filter 64 is handled. This is an implementational detail which will be clear to the person skilled in the art.

Another area of logic optimisation is in the filters 40 (Fig. 5) that generate the lower-level mip-map. If the compression scheme is of a type which uses an index to look up a code book, such as in VQ or Palletised (see above), then in this case the texture components can be arranged in such a way as to enable ease of lower mip-map generation. That is, if the code book entries are generated by evenly sampling the uncompressed texture over its color range, the indexes themselves can be used as the input to the mip-map filters to generate the new lower-level mip-map. The resulting index will then point to the closest code book equivalent of the filtered texture. The bit width of the filtering arithmetic on the indexes (compressed texture) is much smaller than had the filter been applied to the uncompressed texture.

Such an arrangement is illustrated in Figure 10 of the drawings. This is based on Figure 7, though it could of course also include the modification of Figure 9.

Figure 10 shows how the filter 66 now appears inside the decompression unit 62. Each decompression unit 62 has an index lookup section 92 connected to the output of the allocator 82, to provide indices which are filtered by the filter 66 before being applied to a codebook lookup section 94 where the filtered indices are used to find the corresponding codebook portion.

Figure 11 diagrammatically illustrates the relationship between the compressed code values and the

- 22 -

colors they represent. The diagram is assumed to be a part of the color triangle representing all possible colors on a two-dimensional plane. Two colors C1 and C2 are denoted as principal colors. They define the ends of a line on which other intermediate colors C11 to C1i lie. These other colors can therefore be formed by taking an appropriate weighted average of the colors C1 and C2. The code values for the colors C11 to C1i are likewise defined by averaging the code values of the colors C1 and C2.

The normal way of producing the intermediate colors is to start with the compressed code values of the colors C1 and C2 and to determine the actual color values of the colors C1 and C2 to the accuracy of the system, which may require 16 or even 24 bits per color. A weighted average is then performed on the 16 or 24 colors values thus obtained. However, we have appreciated that when the relationship between the colors and their code values is defined in the way just described, it is possible to average the code values first and then subsequently to convert the averaged code value thus obtained to the nearest available color. This means that the averaging operation no longer has to be done with 16 or more bits of data, but can now be done with just the two or so bits which are required to define the different compressed code values in use.

This lower mip-map optimisation technique can also be applied to Direct X compressed textures [ref. 14]. Here the two primary colors and the interpolated intermediate values pointed to by indexes are spaced evenly apart. Figure 12 shows how 2-bit indexes are mapped to 16-bit texture colors. It is seen that the 2-bit indexes themselves can be filtered instead of the full 16-bit value. This represents much less logic and therefore less overall cost.

- 23 -

In summary, the illustrated method of generating texture data for use in texturing an image, is seen to comprise first representing texture data by arbitrary compressed codes, in which selected compressed code values define principal colors and other compressed code values define colors which can be formed by selected weighted averages of principal colors, the corresponding code values also being weighted averages of the code values of the selected principal colors. Then an output texel is interpolated from a plurality of input texels, with the interpolating step being effected using compressed code values. The code values are subsequently decompressed to give the actual color values.

This method finds application for other purposes than just in the lower-level mip-map generator illustrated. It can be used whenever it is desired to generate intermediate colors which are held in compressed form, provided that the compressed codes bear a linear relationship which parallels that of the actual colors themselves. In particular, it can be used in the original generation of the mip-maps held in the memory 22.

The embodiments of the invention which have been described and illustrated provide various improvements over the known systems. In particular, efficient use is made of memory bandwidth for trilinear filtering, especially when using texture compression caches. By generating the lower-level mip-map data from compressed upper-level mip-map data as it is required, accesses across page breaks are reduced. A quad cache arrangement can be used to guarantee one trilinear filtered pixel per clock period. The operation of the decompression logic is improved by using dynamic decompression resource allocation. Finally, the unification of the lower-level mip-map generation with the decompression logic provides a system with relatively low overhead.

- 24 -

It will be appreciated that many modifications may be made to the systems described and illustrate which represent only selected and presently preferred embodiments of the invention.

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- 25 -

CLAIMS

1. A texturing system for use in a three-dimensional imaging system, and comprising:

memory means (22) for storing mip-map data for use in
5 texturing an image, the mip-map data comprising a
hierarchical series of mip-maps of different levels of
decreasing resolution;

input means (26) for receiving input data indicating
the type of mip-map data required and the level of the
10 mip-map or mip-maps from which the data is to be taken;

control means (24) coupled to the input means and to
the memory means for retrieving from memory the mip-map
data required in accordance with the input data; and

cache means (30;60) coupled to the control means for
15 storing portions of mip-map data retrieved from memory and
relating to a selected mip-map level; and

lower-level mip-map generator means (36;66) coupled
to the cache means for generating portions of the mip-map
next below in the hierarchical series of mip-maps of which
20 portions are held in the cache means;

trilinear interpolator means (34;64) coupled to the
cache means to receive mip-map data from one level of
mip-map and to the lower level mip-map generator to
receive mip-map data from the mip-map next below in the
25 heirarchical series and to interpolate an output texel
from input texels from the two received mip-map levels.

2. A texturing system according to claim 1, including
decompression means (32;62) for decompressing mip-map
data, the mip-map data being stored in the memory means in
30 compressed form.

3. A texturing system according to claim 2, in which the
decompression means (32;62) is connected with its input

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- 26 -

coupled to the cache means and its output coupled both to the trilinear interpolator means and to the lower-level mip-map generator means.

4. A texturing system according to claim 2 or 3, in
5 which there are four cache means (60) and four
decompression means (62) arranged in parallel.

5. A texturing system according to claim 2, 3 or 4,
further comprising allocating means (82) between the cache
means (60) and the decompression means (62), for
10 allocating the outputs of different caches to selected
ones of the decompression means.

6. A texturing system according to any preceding claim,
in which the lower-level mip-map generator means comprises
four interpolators which operate on 16 texels from the
15 mip-map held in the cache means to provide four texels as
from the next lower mip-map.

7. A method of texturing for use in three-dimensional
imaging, and comprising the steps of:

storing in memory mip-map data for use in texturing
20 an image, the mip-map data comprising a hierarchical
series of mip-maps of different levels of decreasing
resolution;

receiving input data indicating the type of mip-map
data required and the level of the mip-map or mip-maps
25 from which the data is to be taken;

retrieving from memory the mip-map data required in
accordance with the input data; and

storing in a cache portions of mip-map data retrieved
from memory and relating to a selected mip-map level; and

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- 27 -

generating in real-time portions of the mip-map next below in the hierarchical series of mip-maps of which portions are held in the cache means.

interpolating an output texel from input texels from
5 the mip-map level stored in the cache and the mip-map next below in the heirarchical series generated in real time.

8. Apparatus for generating texture data for use in texturing an image, comprising the steps of:
10 means for representing texture data by arbitrary compressed codes, in which selected compressed code values define principal colors and other compressed code values define colors which can be formed by selected weighted averages of principal colors, the corresponding code
15 values also being weighted averages of the code values of the selected principal colors; and

interpolating means for interpolating an output texel from a plurality of input texels;
characterised in that:
20 the interpolating means effects the interpolation using compressed code values.

9. A method of generating texture data for use in texturing an image, comprising the steps of:
representing texture data by arbitrary compressed
25 codes, in which selected compressed code values define principal colors and other compressed code values define colors which can be formed by selected weighted averages of principal colors, the corresponding code values also being weighted averages of the code values of the selected
30 principal colors;

interpolating an output texel from a plurality of input texels;
characterised in that:

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- 28 -

the interpolating step is effected using compressed
code values.

the interpolating step is effected using compressed
code values.

1 / 9

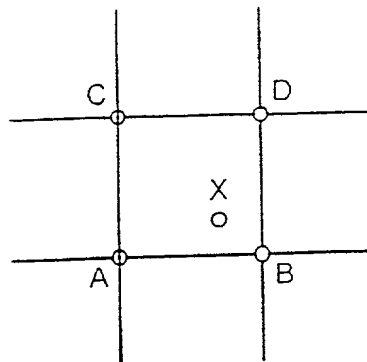


FIG. 1

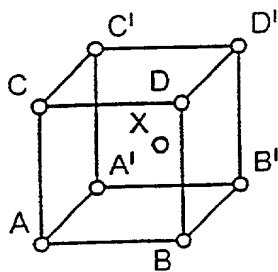


FIG. 2

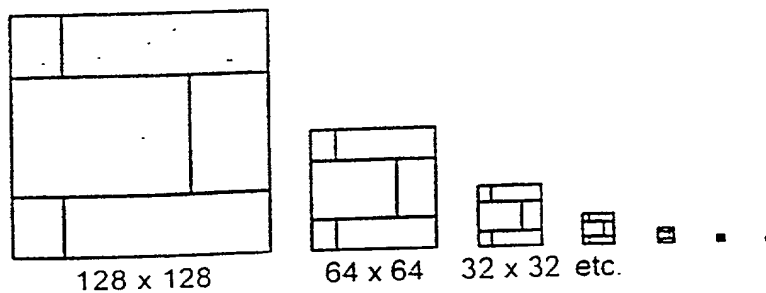


FIG. 3

2/9

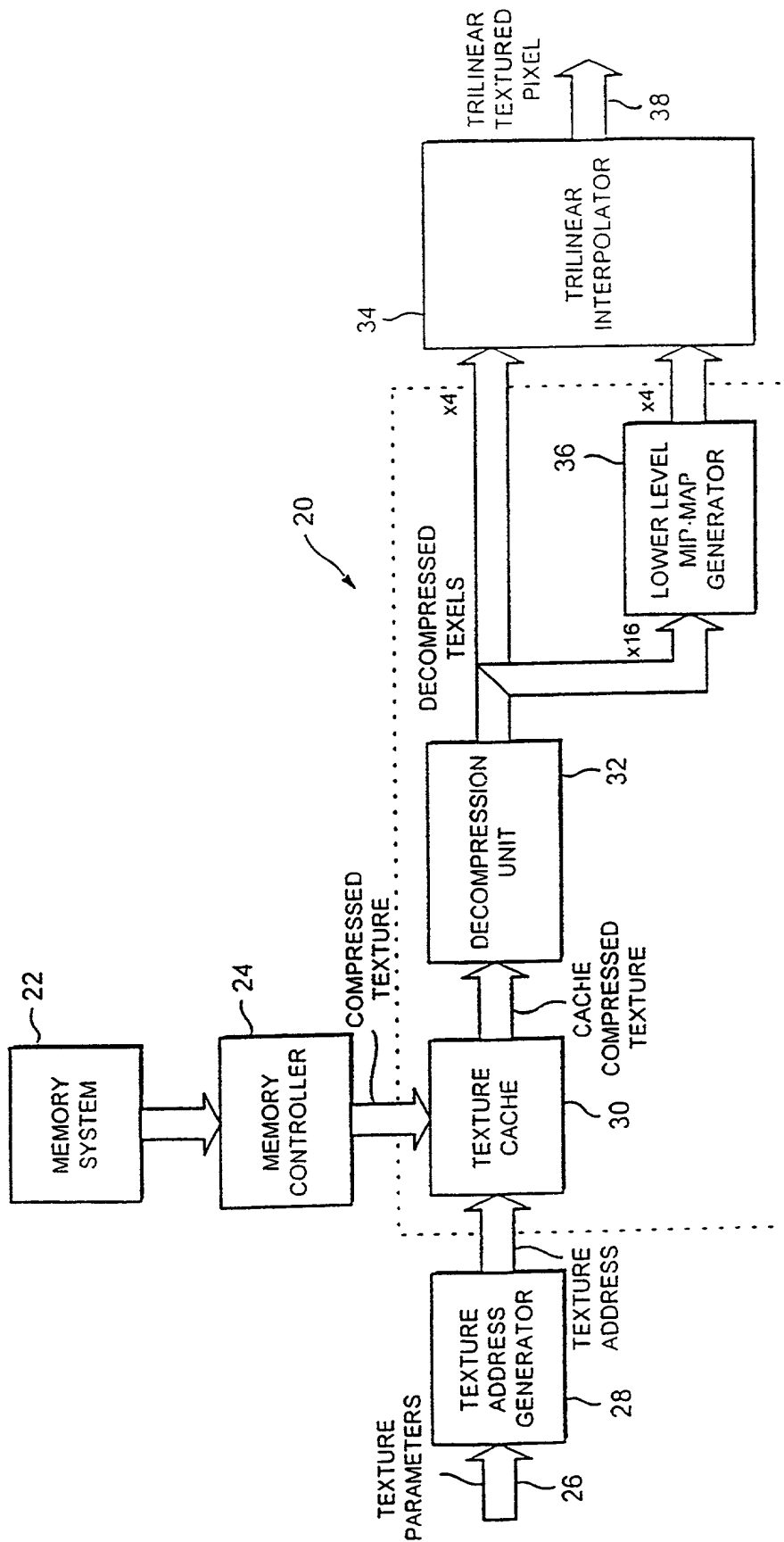


FIG. 4

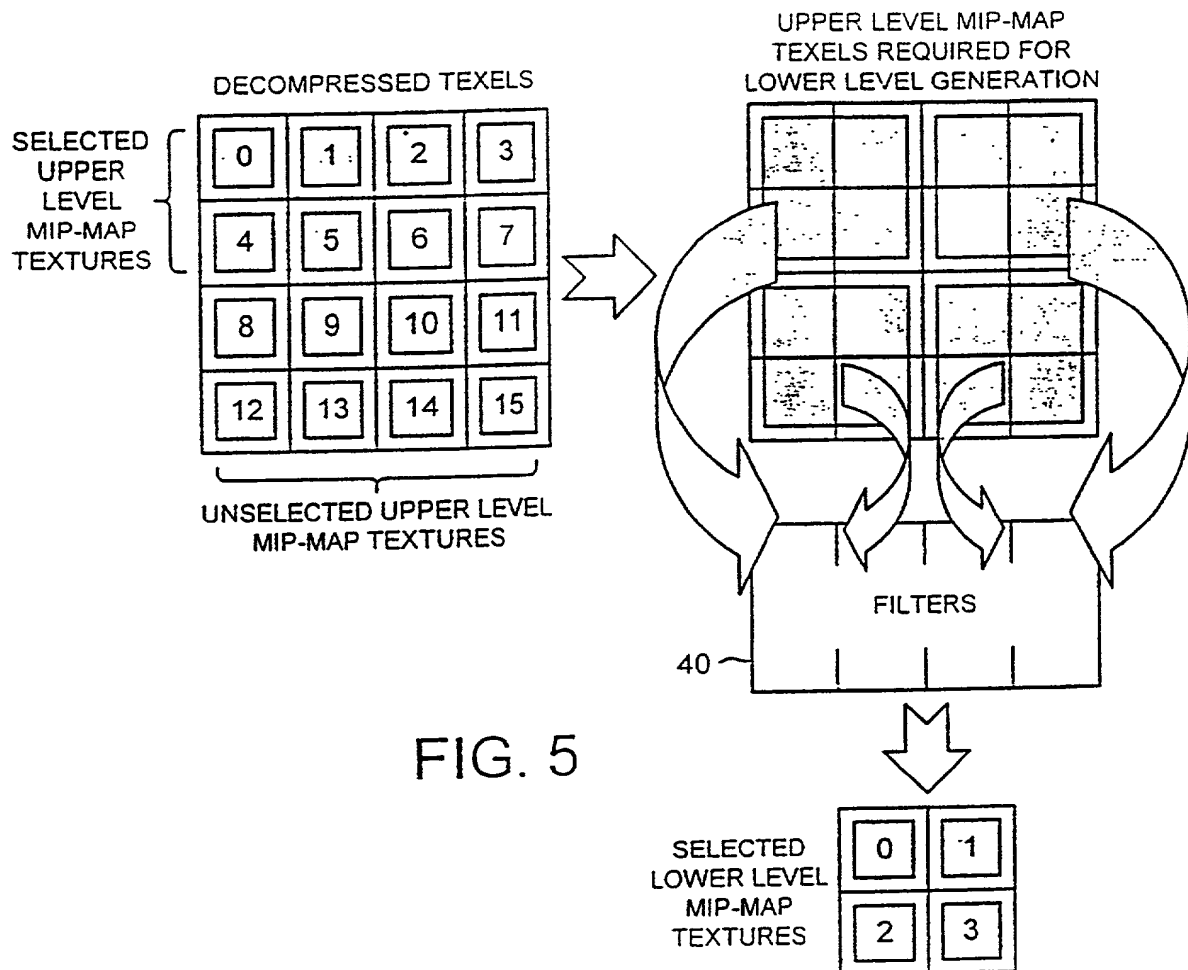


FIG. 5

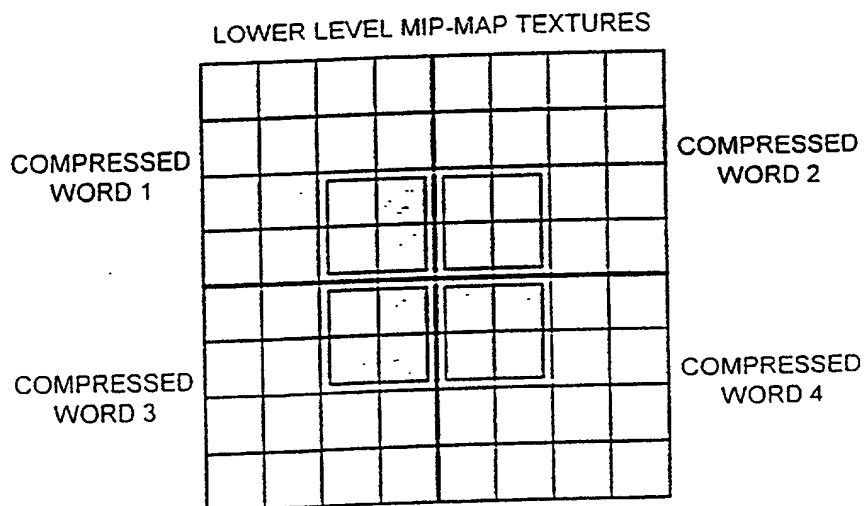
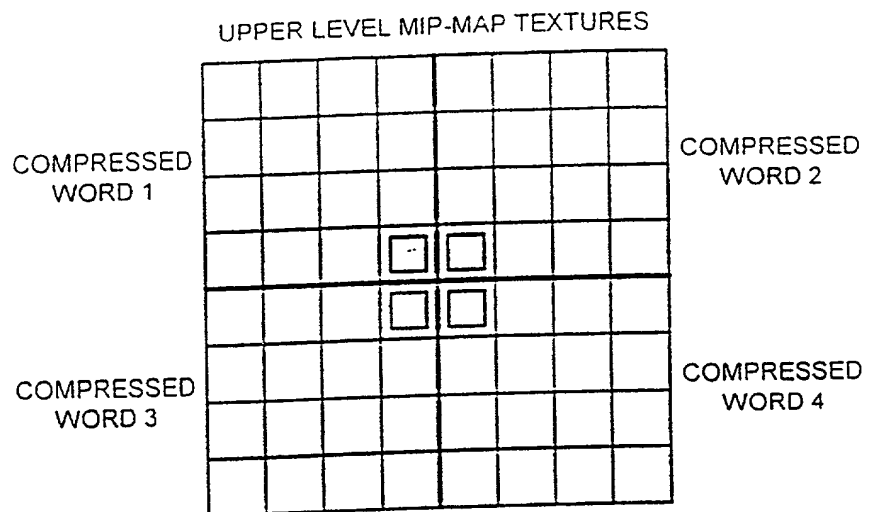
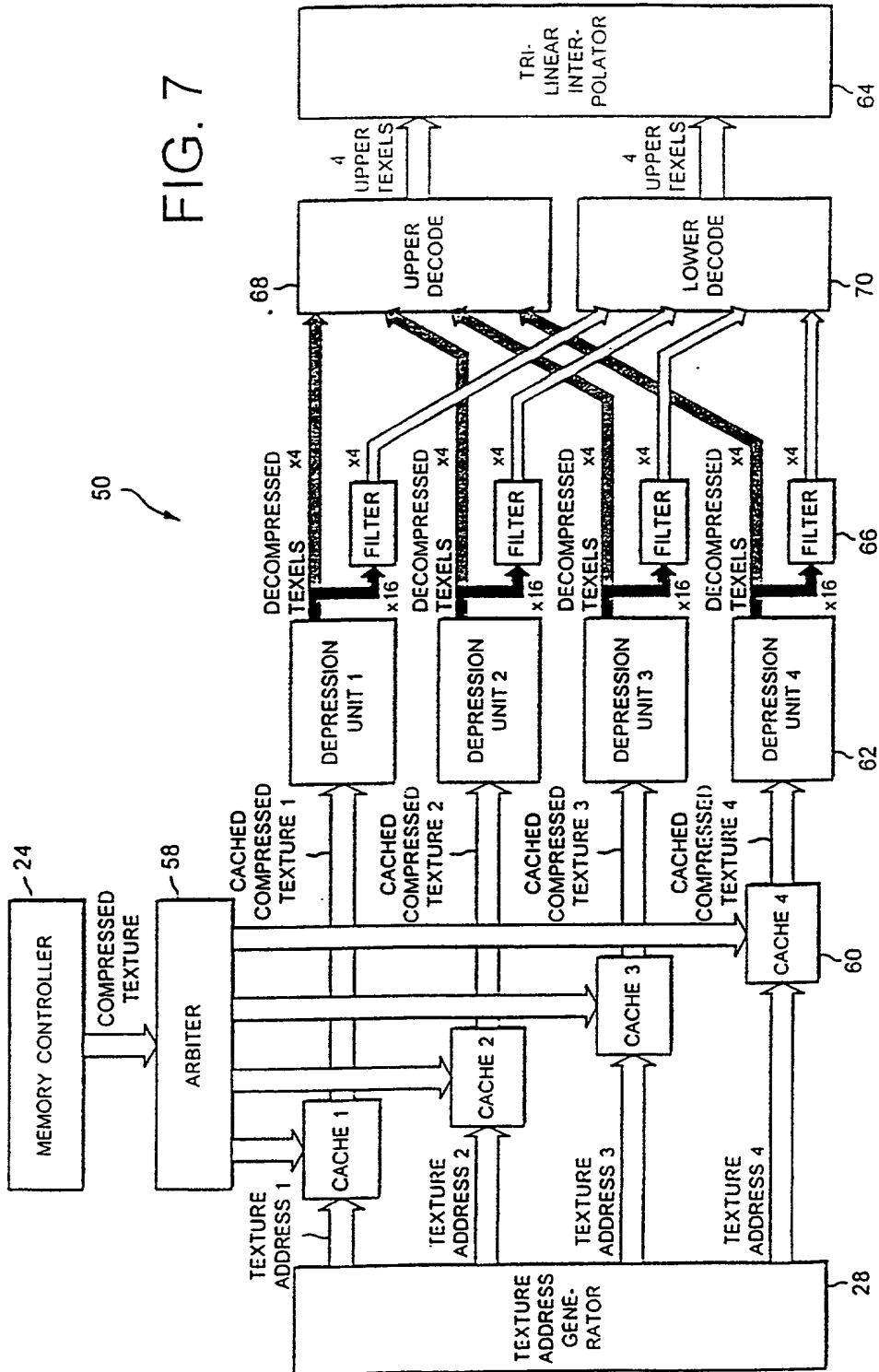


FIG. 6

FIG. 7



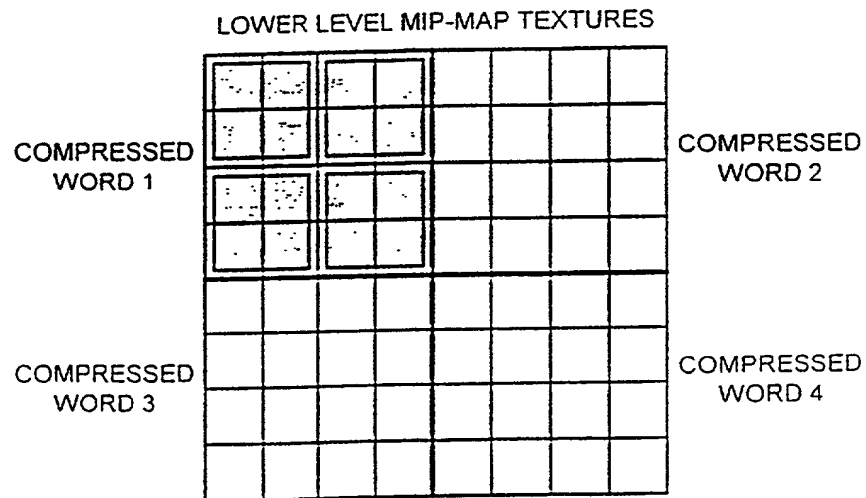
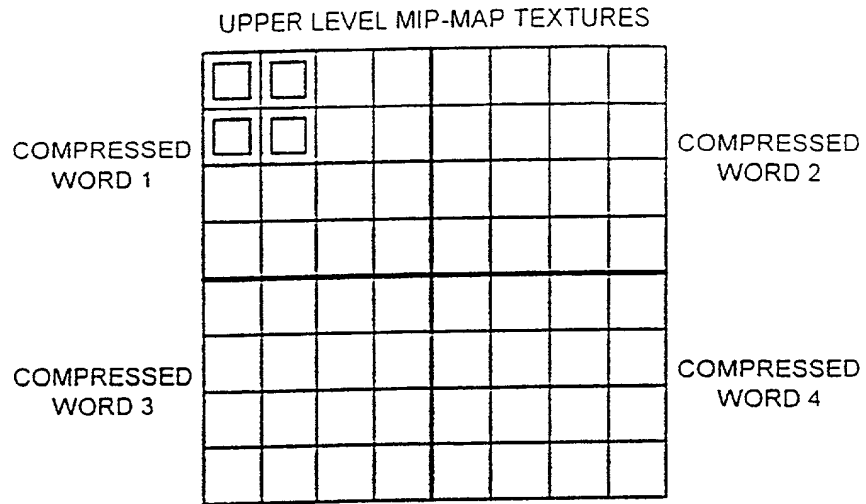
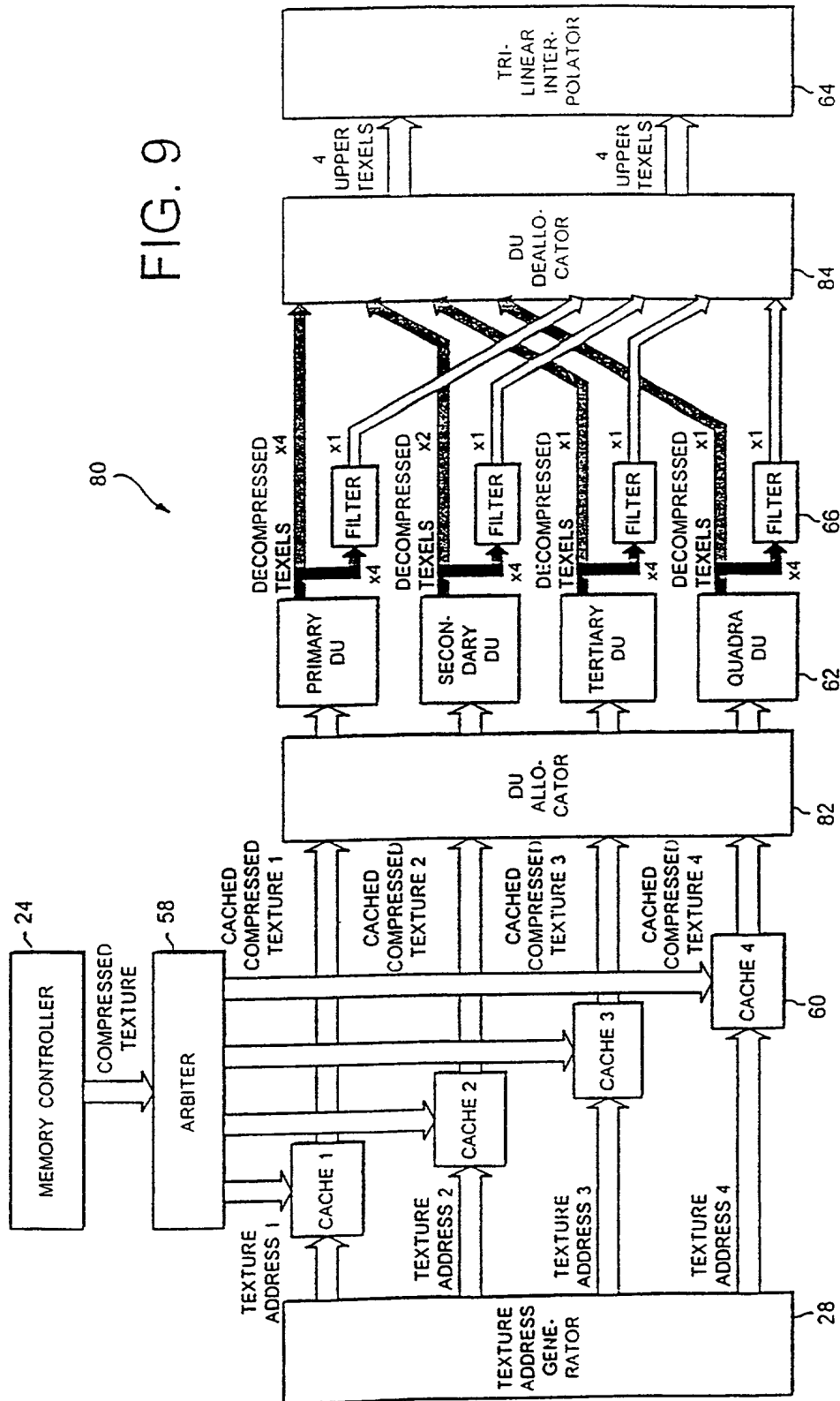


FIG. 8

FIG. 9



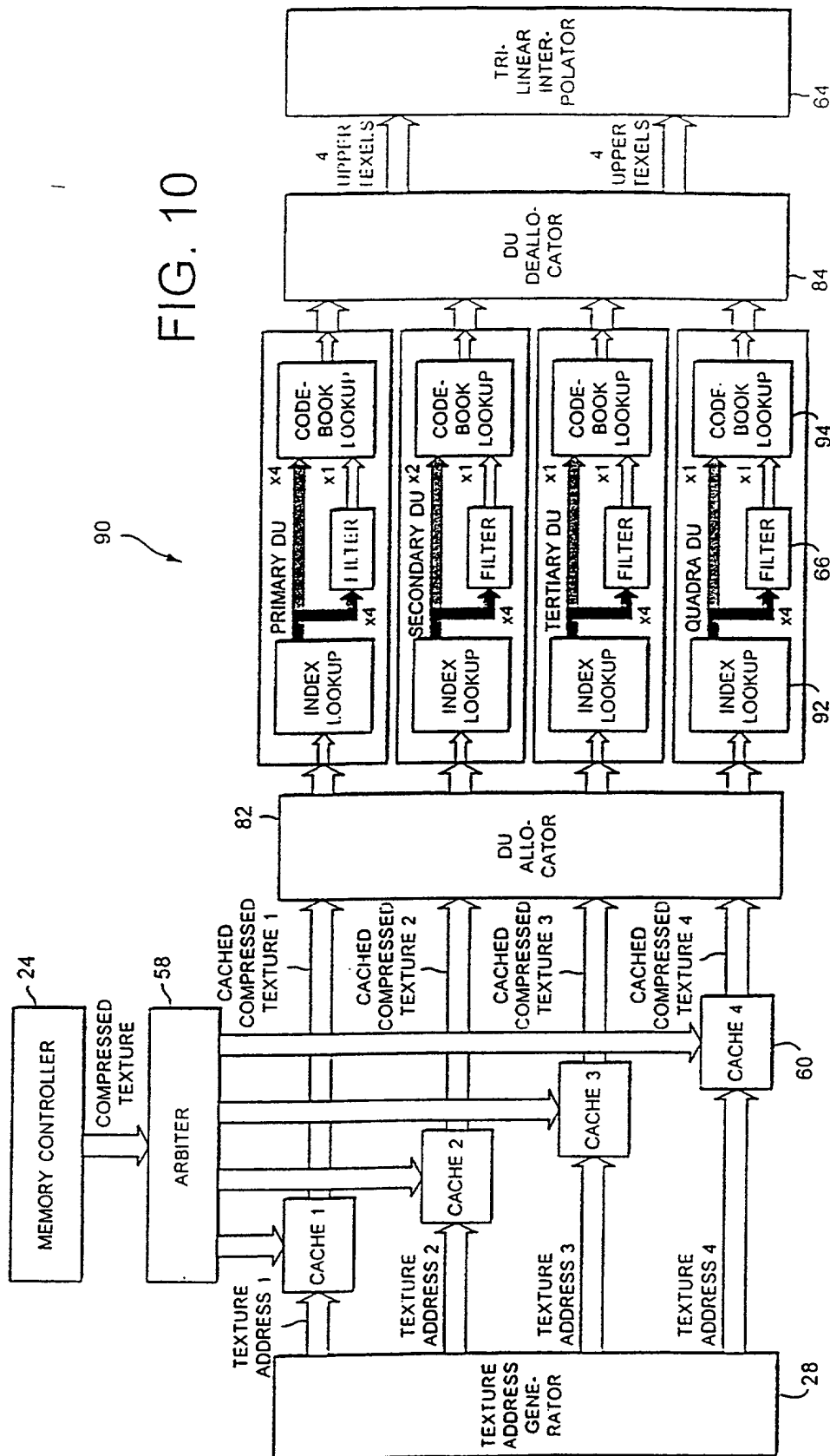
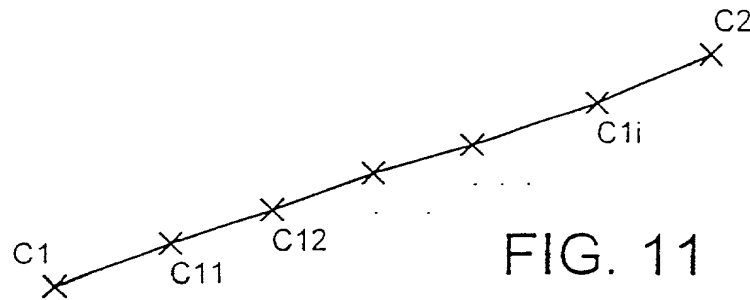


FIG. 10



2 BIT INDEXES

3	2	2	3
2	1	0	2
2	0	1	2
3	2	2	3



16 BIT COLOUR

- INDEX 0
- INDEX 1
- INDEX 2
- INDEX 3

FIG. 12

DECLARATION FOR PATENT APPLICATION

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated next to my name,

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled TEXTURING SYSTEMS FOR USE IN THREE-DIMENSIONAL IMAGING SYSTEMS,

the specification of which

_____ is attached hereto
or

X was filed on November 8, 1999 as United States Application No. or PCT International Application No. PCT/GB99/03711 and was amended on _____ (If applicable)

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, §119(a)-(d) or §365(b) of any foreign application(s) for patent or inventor's certificate, or §365(a) of any PCT International application which designated at least one country other than the United States, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or PCT International application having a filing date before that of the application on which priority is claimed.

<u>Prior Foreign Application(s)</u>			<u>Priority Not Claimed</u>	<u>Certified Copy Attached</u>	
<u>9824407.2</u> (Number)	<u>United Kingdom</u> (Country)	<u>6 November 1998</u> (Day/Month/Year)	_____	Yes _____	No <u>X</u>
_____ (Number)	_____ (Country)	_____ (Day/Month/Year)	_____	Yes _____	No _____
_____ (Number)	_____ (Country)	_____ (Day/Month/Year)	_____	Yes _____	No _____

I hereby claim the benefit under Title 35, United States Code, §119(e) of any United States provisional application(s) listed below:

<u>(Application Serial No.)</u>	<u>(Filing Date)</u>
<u>(Application Serial No.)</u>	<u>(Filing Date)</u>

I hereby claim the benefit under Title 35, United States Code, §120 of any United States application(s) or §365(c) of any PCT International application designating the United States, listed

Page 2

PTO/SB/01(12/97)

below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of Title 35, United States Code, §112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application:

(Application Serial No.)	(Filing Date)	(Parent Patent Number) (if applicable)
--------------------------	---------------	---

(Application Serial No.)	(Filing Date)	(Parent Patent Number) (if applicable)
--------------------------	---------------	---

As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith:

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Fax: (616) 381-5465	Brian R. Tumm	Reg. No. 36 328

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full name of sole or first inventor Simon PEARCE

Inventor's signature SPearce

3/5/01
Date

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Additional inventors are being named on the _____ supplemental additional inventor(s) sheet(s).

X This declaration ends with this page.